3.3.6 Smart Stations

Site surveying is increasingly being carried out using GNNS and Total Station equipment. Integrated survey rovers (called *Smart Stations*) combine the GNSS and Total Station to significantly improve the efficiency of survey work (Figure 3.13). It ensures that in case of obstruction in horizontal visibility, GNSS antenna is connected to the Total Station, and all operations of GNSS observations are performed through the keyboard of the Total Station. Where GNSS does not receive good signals from the satellites due to vertical obstructions, Total Station is used. These latest developments in Total Stations are also capable to provide data for building information modeling (BIM) and virtual design and construction.

Although the use of GNSS is increasing, but the Total Stations are one of the predominant instruments used on site for surveying, and will be used in future along with other surveying equipment to provide accurate and faster data collection approaches. Developments in both technologies (GNSS and Total Station) will find a point where devices can be made that complement both the methods.

Figure 3.13 Smart station (Total Station and GNSS combined)

3.3.7 Uses of Total Stations

(a) To measure horizontal and vertical angles.
(b) To obtain the horizontal distance, slope distance and vertical distance between the points.
(c) To get the 3-D co-ordinates (x, y, z) or (northing, easting and elevation) of surveyed points.
(d) To locate the points at a pre-determined distance.
(e) Plotting of contours
(f) Creating detailed maps
(g) Carrying out the control surveys
(h) To estimate the excavations
(i) In crime scene investigations to take measurements of the scene
(j) Used to fix the missing pillars
(k) Remote Distance Measurement (RDM)
(l) Missing Line Measurement (MLM)
(m) Remove Elevation Measurement (REM)

3.3.8 Advantages and disadvantages of Total Stations

Advantages:

(a) Field work is carried out very fast with a Total Station, saving time in the field.
(b) Setting up of the instrument on the tripod can be done easily and quickly by laser plummet and auto levelling facility.
(c) The accuracy of measurements is much higher as compared to other conventional surveying instruments.
(d) The measured data can be saved and simultaneously transferred to the computer for subsequent use by the software.
(e) Since data recording is automatic, no writing or recording errors is committed.
(f) Correction for temperature and pressure can also be made in the field data.
(g) Accuracy of measurement is high.
(h) Calculation of coordinates is very fast and accurate.
(i) Contour intervals and scales can be changed in no time.
(j) Software can be employed for map making, plotting contour and cross-sections, and 3D models.

Disadvantages:

(a) The cost of the instrument is higher than the other surveying instruments.
(b) Checking for errors or other things during the operation is slightly difficult.
(c) Skilled surveyors are required to handle since it is a sophisticated instrument to operate.

3.3.9 Calibration of Total Stations

Total Stations are worldwide known for their highest precision, reliability and durability. Due to temperature changes, shock or vibrations, instrument precision can change slightly over time. Even the most careful and precise assembly process, however, can result in small deviations which can lead to so called instrument errors. The modern Total Stations, like any other equipment, will provide errors in their measurements due to instrument error which is to be checked on a regular basis using procedures outlined in their manuals. Some instrumental errors are eliminated by taking observation on two faces of the Total Station and taking the average of both, but because one face measurements are common in the field, it is necessary to determine the magnitude of instrumental errors and correct them.

To further minimise these errors, the instrument can be calibrated by the user from time to time (Reda and Bedada, 2012). It is not necessary to send the instruments back to manufacturer for re-calibration. Almost all the modern total stations can be re-calibrated by the users. The user calibration feature is called "Check & Adjust" or just "Adjust" depending on the field software. The different Check & Adjust procedures are very simple to use. If they are followed carefully and precisely, the parameters will be correctly determined by the instrument itself. The instrument does a validity check of the calibration values and warns the user in case of mis-calibration. The calibration values will be stored in the instrument and automatically applied to all subsequent measurements when the tilt compensator and horizontal corrections are activated.

For Total Stations, instrumental errors are measured and corrected using electronic calibration procedures that may be carried out at the site. The electronic calibration procedure is preferred as compared to the mechanical adjustments that used to be done in the labs by trained technicians. Calibration parameters of the instrument usually change because of transportation of equipment, jerking in the field, temperature changes and rough handling, and therefore a high-precision Total Station requires electronic calibration, particularly (i) before using the instrument for the first time, (ii) after long storage periods, (iii) after rough or long transportation, (iv) after long periods of work, and (v) when the temperature changes appreciably.

3.3.10 Errors in Total Station measurements

Like any device, Total Stations also have some sources of error which can affect the surveying observations. All theodolites measure angles with some degree of imperfection, resulting from the fact that no mechanical device can be manufactured with zero error. With the advent of electronic theodolites, mechanical errors are still present but are related in a different way. So, it is important to understand the concepts behind the adjustments for errors that Total Stations now make (Garg, 2021).

1. Circle eccentricity error

Circle eccentricity errors occur when the theoretical center of the mechanical axis of the theodolite does not coincide exactly with the center of the measuring circle. The magnitude of error corresponds to the degree of eccentricity and the part of the circle being read. The circle eccentricity errors appear as a sine curve, graphically. This error in the horizontal circle can always be compensated by taking the measurement on both the faces (opposite sides of the circle) and taking the mean value. However, the vertical circle eccentricity error cannot be compensated this way, since the circle moves with the telescope. More sophisticated techniques are required; (1) Some theodolites are individually tested to determine the sine curve for the circle error in that particular instrument. Then a correction factor is added or subtracted from each angle reading to display corrected measurement, and (2) Other instruments employ an angle measuring system consisting of rotating glass circle that makes a complete revolution for every angle measurement. These are scanned by fixed and moving light sensors. The glass circles are divided into equally spaced intervals which are diametrically scanned by the sensors. The amount of time it takes to input a reading into the processor is equal to one interval, thus only every alternate graduation is scanned. As a result, measurements are made and averaged for each circle measurement. This eliminates the scale graduation and circle eccentricity error.

2. Circle graduation error

In the past, circle graduation error was considered a major source of error. For precise measurements, earlier several set of measurements were repeated beginning with 0^0, 90^0, 180^0 and 270^0, and mean value adopted to eliminate the circle graduation error. Current technology eliminates the problem of graduation errors by photo-etching the graduations onto the glass circles and making a precise master circle and photographing it. An emulsion is then applied to the circle and a photo-reduced image of the master is projected onto the circle. When the emulsion is removed and the glass circle is etched with very precise graduations.

3. Horizontal collimation (Line of sight) error

The axial error is caused in Total Station when the line of sight is not perpendicular to the tilting axis. It affects all the horizontal circle readings and increases with the steep sight readings. The error can be eliminated by taking observations on both the faces (left and right). For single face measurements, an on-board calibration function is used to determine '*c'*, the deviation between the actual line of sight and a line perpendicular to the tilting axis (Figure 3.14a). A correction is then applied automatically for all the horizontal circle readings.

4. Tilting axis or Tilt error

The axial errors occur when the titling axis of the Total Station is not perpendicular to its vertical axis. It has no effect on readings taken when the telescope is horizontal, but introduces errors into horizontal circle readings when the telescope is tilted, especially for steep sights. As with horizontal collimation error, this error is also eliminated by taking two face measurements. Alternatively, a tilting axis error '*a*' is measured in a calibration procedure and a correction is applied to all the horizontal circle readings (Figure 3.14b). If the value of '*a*' is large, the instrument should be returned to the manufacturer for calibration.

5. Compensator index error

If the Total Station is not carefully levelled, this error cannot be eliminated by taking both the face readings. Several Total Stations are equipped with a compensator that will measure the residual tilt of the instrument, and subsequently apply the corrections to both the horizontal and vertical angles. Normally, all the compensators will have a longitudinal error '*l*' and traverse error '*t*' known as *zero point errors* (Figure 3.14c). These are averaged using both the face readings, but for a single face reading, it must be determined by the calibration function of Total Station.

6. Vertical collimation or Vertical index error

A vertical collimation error is present in a Total Station if the 0º to 180º line in the vertical circle does not coincide with its vertical axis. This zero point error is present in all vertical circle readings and similar to horizontal collimation error, and it is eliminated by taking both the face readings. Else, it is eliminated by determining '*i*' (Figure 3.14d).

7. Vertical circle error

It is important to check the vertical circle indexing adjustment on Total Station on a routine basis. When direct and indirect zenith angles are measured to the same point, sum of the two angles should be equal to 360°. Over continuous use, the sum of these two angles may diverge from 360°, and consequently cause errors in vertical angle measurements. While, averaging the direct and indirect zenith angles easily eliminates this error, on many jobs it may not be cost effective to take two readings. Acceptable accuracy may still be maintained for many applications with only a direct reading; as long as the index error is kept to a minimum by periodically performing a vertical adjustment. Most Total Stations are provided with some type of electronic adjustment to correct the vertical circle indexing error. This adjustment takes just a few seconds and will provide good vertical angle readings with just one measurement. The adjustment can be made as per explanation given in manufacturer's manual.

8. Pointing errors

Pointing errors are due to both human's abilities to point the instrument and environmental conditions limiting the clear vision of the observed target. The best way to minimize the pointing errors is to repeat the observations several times and use the average value.

9. Uneven heating

Direct sunlight can heat one side of the instrument enough to cause small errors. For the highest accuracy, the instrument is shaded with an umbrella or a shaded spot is selected to set up the instrument.

10. Vibrations

Avoid setting up the instrument at locations that are subject to vibration, such as the site near airports, railway tracks. Continuous vibrations can cause the compensator unstable.

11. Atmospheric errors

The Total Stations are generally standardized at a specific temperature and pressure. When measurement conditions deviate from either then a proportional correction must be applied. Meteorological data corrections to observed slope distances may be significant for longer distances, so they need to be applied. The refractive indices of electromagnetic waves in air are functions of air temperature, atmospheric pressure and the partial pressure of water vapour. But, light waves and microwaves react somewhat differently to varying atmospheric conditions. These errors can be removed by applying an appropriate atmospheric correction model that takes care of different meteorological parameters from the standard (nominal) one. This is normally done by the Total Station, as it requires some necessary information (temp and pressure) from the operator. For most topographic surveying over short distances, nominal (estimated) temperature and pressure data is acceptable for input into the data collector. Instruments used to measure the atmospheric temperature and pressure, such as thermometers and barometers, must be periodically calibrated.

12. Optical plummet errors

The optical plummet must be periodically checked for misalignment. This would also include Total Stations with laser plummets.

13. Adjustment of prism poles

When using prism poles, precautions should be taken to adjust the leveling bubble. Bubbles tube can be examined by standard tests.

14. Height of standards error

To plunge the telescope of Total Station through a truly vertical plane, the telescope axis must be perpendicular to the vertical axis. The horizontal collimation and height of standards errors are correlated, and can magnify or offset one another. Horizontal collimation error is usually eliminated before checking for height of standards. Height of standards error is checked by pointing to a scale the same zenith angle above a 90^0 zenith in "face-one" and "face-two." The scales should read the same value in both the faces.

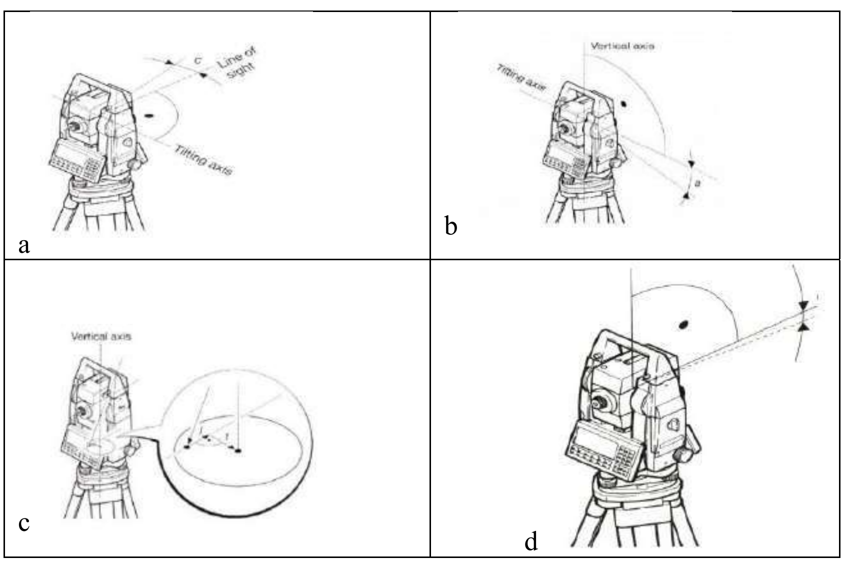

Figure 3.14 Depiction of various errors from Total Station (Source: https://www.brainkart.com/article/Sources-of-Error-for-Total-Stations_4653)

3.4 Global Positioning Systems (GPS)

The navigation systems in some form or the other have been in use since the civilizations. Human-beings have always been interested to know where they are, where they are going, and how they are going to get there, and back again to their destination, using some appropriate path. So, several crude methods have been developed in the past. In modern era, GNSS (Global Navigational Satellite System), which receives signals from the all the satellites, is used for precise navigation (Garg, 2019). The GNNS broadcasts precise, synchronized timing signals to provide precise position, velocity and time.

The GPS was developed by the Department of Defence (DoD), USA, which is a part of Global Navigation Satellite System (GNSS), primarily to provide precise estimates of position, velocity and time to the U.S. military. In 1973, the US decided to establish, develop, test, acquire, and deploy a first space-borne GPS, resulting in the NAVSTAR (Navigation Satellite Timing and Ranging) GPS. Initial satellites were launched between 1974 and 1977 for use in precision weapon delivery (Herring, 1996). In the early 20th century, ground-based radio-navigation systems were developed. Although, the GPS was initially developed for military applications, but over a period of time, the civil applications of GPS and GNSS have grown at an alarming rate. In the 1980s, the government made the system available for civilian use. It has brought a great technological revolution in surveying where the exact position of any object or phenomena is to be captured.

The European Union developed a system, known as GALELIO navigation satellites. Indian system is known as the IRNSS (Indian Regional Navigation Satellite System), using its seven satellites, which will beam accurate navigation signals over India and up to 1,500 km from its borders. India's own GPS NavIC ('Navigation with Indian Constellation' whose Hindi meaning is '*sailor*' or 'navigator') is the operational name of IRNSS. China has created the BeiDou (Compass) Navigation Satellite System; while the regional service has already been launched. The QZSS (Quasi-Zenith Satellite System) Japan, signal is designed in such a way that it is interoperable with GPS. It improves visibility and DOP (Dilution of Precision) in dense urban area, and provides messaging system during disasters. It provides augmentation data for sub-meter and centimeter level position accuracy.

The GNNS is primarily a navigation system receiving signal from all visible satellites for real-time positioning. The GNSS broadcasts the precise, synchronized timing signals to provide precise estimates of position, velocity and time. With the transformation from the ground-to-ground survey measurements to ground-to-space measurements made possibly by GNSS, this technique overcomes several limitations of ground surveying methods, like the requirement of intervisibility of survey stations, dependability on weather, difficulties in night observations, etc. These advantages over the conventional techniques and the economy of operations make GNSS the most promising surveying technique. With the high accuracy achievable with GNSS in positioning of points, this unique surveying technique has found important applications in diverse fields. Other advantages include (i) increase in usable space vehicles, signals and frequencies, (ii) increase in availability and coverage, (iii) more robust and reliable services, (iv) higher accuracy even in bad conditions, (v) offers less expensive high-end services, (vi) applies better atmospheric correction, and (vi) use in new and applications, such as atmosphere related, short message broadcasting, search and rescue applications, determine soil moisture, wind velocity, sea wave height etc.

Surveying and mapping fields have greatly benefitted with the availability of GPS and GNSS, such as highways, railroads, mining/geology, agricultural, power, telecommunications, health, law enforcement, emergency, crustal movement, etc. The GNSS offers the advantages of accuracy and speed, while collecting data in the field. The other advantage is to provide exact position of objects anytime, anywhere, and in any weather condition. The benefits of using GNSS for mapping and modeling include improved productivity, fewer limitations (such as open to sky requirements), and faster delivery of 3D coordinates. The other technological revolution the GNSS has provided for multiple applications, such as locating a petrol pump, restaurant, cinema hall etc. World-wide, there are a large number of users of GNSS enabled gadgets, like vehicles, mobile phones, wrist watches etc., used for a variety of utility. Today GNSS is considered as a global leader in navigational systems all over the world.

3.4.1 Technical terms in GNSS

Latitude: It is an angular measurement made from the center of the Earth to north or south of the equator. It comprises the north/south component of the latitude/longitude coordinate system, which is used in GNSS data collection.

Longitude: It is an angular measurement made from the center of the Earth to the east or west of the Greenwich meridian. It comprises the east/west component of the latitude/longitude coordinate system, which is used in GNSS data collection.

Datum: The GNSS receivers are designed to collect positions relative to the WGS-84 datum, however the user has the option of defining the datum in which the data will be collected. Users must be familiar with the datum before data collection. For example, for most GIS applications, the WGS-84 datum is similar to the NAD-83 datum, however NAD-27 is significantly different from the NAD-83 datum.

Ellipsoid: An ellipsoid is the 3-D shape that is used as the basis for mathematical modelling of Earth surface. The ellipsoid is defined by the lengths of minor axes (polar axis) and major axes (equatorial axis).

Geoid: A mathematical surface of constant gravitational potential that approximates the sea level, or the equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level.

Satellite constellation: The arrangement in space of a set of satellites.

NAVSTAR (NAVigation Satellite Timing And Ranging) System): The formal name given to the United States NAVigation Satellite Timing And Ranging (NAVSTAR) System. which comprises of GPS satellites, monitoring stations, and master control station.

Ephemeris: The current satellite position predictions that are transmitted from a GNSS satellite in the NAVDATA message.

Rover (GNSS) Receiver: Any mobile GNSS receiver and data collector used for determining location in the field. A roving GNSS position can be differentially corrected relative to a stationery base GNSS receiver.

L1 Frequency: The primary L-band carrier used by GNSS satellites to transmit satellite data in frequency 1575.42 MHz. It is modulated by C/A code, P-code and a 50 bit/second navigation message.

L2 Frequency: The secondary L-band carrier used by GPS satellites to transmit satellite data in frequency 1227.6 MHz. It is modulated by P-code and a 50 bit/second navigation message.

L5 Frequency: The L5 signal operates at 1176.45 MHz which is planned to be used to improve accuracy for civilian use, such as aircraft precision approach guidance. The GNSS has fifteen satellites with L5 available and Galileo with 24 all of which are currently using L5.

Epoch: The measurement interval of a GNSS receiver.

Dual-frequency (GNSS) Receiver: A type of GNSS receiver that uses both L1 and L2 signals from satellites. A dual-frequency GNSS receiver can compute more precise position fixes over longer distances and under more adverse conditions by compensating for ionospheric delays. The receivers are now available which can also receive signal in L5 wavelength, in addition to L1 and L2.

Multi-constellation and Multi-frequency (GNSS) Receiver: Multi-frequency GNSS receivers are used for reliable positioning down to the centimeter level. Among various professional-grade GNSS receivers, there is variability in the satellite constellations and signals that a receiver can access. Those receivers that have access to the highest number of constellations and signals from, for example, Galileo, QZSS, BeiDou, offer the best positioning availability, accuracy and resilience even in challenging environments. A simple GPS receiver only makes use of one global navigation satellite system, while multi-constellation GNSS receivers get information from many such systems at the same time.

Ephemeris: The prediction of current satellite position that is transmitted to the user in the data message.

Data Message: A message included in the GNSS signal, which reports a satellite location, clock correction, and health. It also includes information on other satellites' health and their approximate positions.

Pseudorandom Noise or Number (PRN): A signal that carries a code that appears to be randomly distributed, like noise, but can be exactly reproduced. The PRN codes have a low auto-correlation value for all delays or lags, except when they are exactly coincident. Each NAVSTAR satellite has its own unique PRN code.

Carrier Phase: The difference between the carrier signal generated by the internal oscillator of a roving GNSS receiver and the carrier signal emitted from a particular GNSS satellite.

Coarse or Acquisition (C/A) Code: A pseudorandom noise (PRN) code modulated onto a L1 signal which helps the GNSS receiver to compute the distance from each satellite. Specifically, the difference between the PRN code generated by the GNSS rover software and the PRN code coming in from the satellite is used to quickly compute the distance to a satellite and the position.

P-Code: The precise code transmitted by the GNSS satellites. Each satellite has a unique code that is modulated onto both the L1 and L2 carrier. The P-code is replaced by a Y-code when Anti-Spoofing is active.

Selective Availability (SA): The artificial and deliberate degradation of GPS satellite signals by the United States Department of Defense. Selective Availability was implemented in view of the national security, but was turned off on May 10, 2000 due to the presence of several sources of various differential correction (DGNSS) messages, which rendered SA obsolete. Earlier the potential error due to SA is between 30 to 100 m.

Signal-to-Noise Ratio (SNR): The signal strength of a satellite is a measure of the information content of the signal relative to the signal's noise. The typical SNR of a satellite at 30^0 is between 47-50 dBHz. The quality of a GNSS position is degraded if the SNR of one or more satellites in the constellation falls below 39. If a satellite's SNR is below the configured minimum SNR, that satellite is not used to compute positions.

Base Station: A base station is comprised of a GNSS antenna and GNSS receiver positioned at a known location specifically to collect data for differential correction. The purpose of the base station is to provide reference data for applying the differential correction on data collected in the field. A base station can be a permanent installation that can be used by multiple users.

VRS (Virtual Reference Station): A VRS system consists of GNSS hardware, software, and communication links. It uses data from a network of base stations to provide corrections to each rover that are more accurate than the corrections from a single base station. To start using VRS corrections, the rover sends its position to the VRS server. The VRS server uses the base station data to model systematic errors (such as ionospheric noise) at the rover position. It then sends correction messages back to the rover.

Initialization of GNSS: Initialization refers to the procedure of telling a GNSS receiver where it is, when it is turned on for the first time. Information required for initialization includes approximate present position in latitude/longitude coordinates, the current local time and date.

Differential Correction: The process of correcting GNSS data collected on a rover with data collected simultaneously at a base station. Because it is on a known location, any errors in data collected at the base station can be measured, and the necessary corrections applied to the rover data. Differential correction can be done in real time, or after the data has been collected by post-processing software.

RTK (Real-Time Kinematic): A real-time differential GNSS method that uses carrier phase measurements for greater accuracy. The RTK measurements can typically yield relative horizontal accuracy of approximately one centimeter.

Accuracy: The degree of conformity with a standard or accepted value. Accuracy relates to the quality of the result, and is distinguished from precision which relates to the quality of the operation by which the result is obtained.

Precision: A measure of the repeatability or uniformity of a measurement. Precision relates to the quality of the operation by which the result is obtained. In order to comply with a specific standard, accuracy results must meet the minimum while complying with the precision required.

Multipath Errors: Errors caused by reflected signals arriving at the GNSS receiver, as a result of nearby structures or other reflective surfaces (e.g., buildings, forest, water). Signals traveling longer paths produce higher (erroneous) pseudorange estimates and, consequently the positioning errors. Some mapping grade GNSS receivers as well as most or all survey grade GNSS receivers have antennas and software capable of minimizing multipath signals.

Atmospheric Delays: The satellite signal slows down as it passes through the atmosphere. The GNSS system uses a model that calculates an average amount of delay to correct for this type of error.

Receiver Clock Errors: A receiver's built-in clock is not as accurate as the atomic clocks onboard the GNSS satellites, therefore, it may have very slight timing errors.

Orbital Errors: Also known as ephemeris errors, these are inaccuracies of the satellite's reported location.

Dilution of Precision (DOP): It is an indication of the quality of the results that can be expected from a GNSS point position. It is a measure based solely on the geometry of the satellites in the sky.

Geometric Dilution of Precision (GDOP): It deals with the overall accuracy, 3D-coordinates and time.

Positional Dilution of Precision (PDOP): It deals with the position accuracy, and 3D-coordinates. A value expressing the relationship between the error in user position and the error in satellite position. Values considered good for positioning are small, such as 3. The GNSS receiver may be set to collect data at a PDOP level of 6 or less. Values greater than 7 are considered poor.

Horizontal Dilution of Precision (HDOP): It deals with the horizontal accuracy, and 2D-coordinates.

Vertical Dilution of Precision (VDOP): It deals with the vertical accuracy, and height.

Post-processing of Data: The processing of satellite data done after it has been collected in order to eliminate the errors, using. Since the location of base station is known, systematic errors can be detected and removed from the rover data.

SBAS (Satellite Based Augmentation System): This term refers to differential GNSS applied to a specific wide area, such as an entire continent. The SBAS comprised of a series of reference stations that generate GNSS corrections which are broadcast to GNSS rovers *via* geostationary satellites. The WAAS and EGNOS, MSAS, GAGAN are some examples of SBAS network.

3.4.2 Basic principle of GPS

The GPS is based on very simple and quite ancient idea of determining the position, e.g., coordinates (x,y,z), given the distances and directions to other surrounding objects whose positions are known (Garg, 2021). Let us consider three objects whose positions (i.e., their coordinates) as well as their distances from the unknown position of the observer are known. The observer's position can now be related to the known distances and positions of objects by using distance equation. Thus, from the known positions of the objects and their distances from observer's position, we get three distance equations involving three unknowns (x,y,z) corresponding to the position of the observer. These three equations can be solved for the three unknowns i.e., x,y,z. The novelty of GNSS lies in the realization of above concept with the technology of late 20^{th} century in a global navigation system. It has the capability to provide estimates of position, velocity and time to an unlimited number of users instantaneously and continuously.

The accuracy of GNSS height measurements depends on several factors but the most crucial one is the undulating shape of the Earth (Xu, 2010). Height can be measured in two ways. The GNSS uses ellipsoidal height (h) above the reference ellipsoid that approximates the Earth's surface. The traditional, orthometric height (H) is the height above an imaginary surface called the geoid (Figure 3.15), which is determined by the Earth's gravity and approximated by MSL. The orthometric height is often referred as the MSL, and can be obtained by subtracting the geoid height (N) from the GNSS height (h) (i.e., H = h - N). The signed difference between the two heights; the difference between the ellipsoid and geoid, is the geoid height (N). Figure 3.15 shows a relationship between the different models; a geoid height (N) is positive when the geoid is above the ellipsoid and negative when it is below.

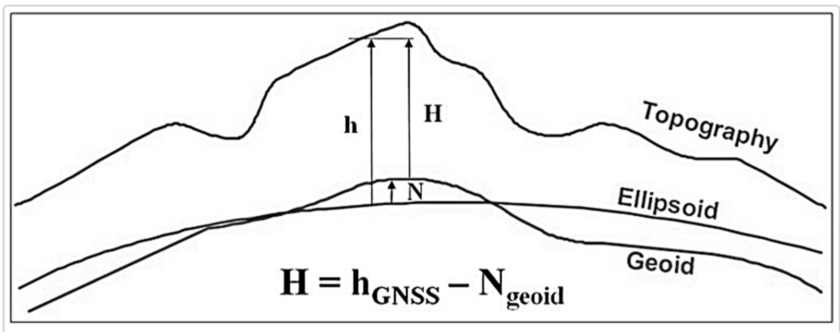

Figure 3.15 The ellipsoidal height, orthometric height and geoid height

In GNSS based determination of observer's position, satellites act as reference points (i.e., known locations) from which receiver on the ground determines its position. By measuring the travel time of the signals transmitted from at least four satellites, the distances between the receiver and satellite will yield accurate position, velocity and time. Though three-range measurements are sufficient but fourth observation is essential for solving the clock synchronization error between the receiver and satellite. The strength of GPS measurement lies in its ability to measure 1/100 of a cycle of a carrier phase is about 2 to 3 mm in linear distance.

The GNSS satellites cover every corner of the Earth; no matter where you are. If at least four satellites are visible at any time, the GNSS observations can be taken. Each satellite regularly transmits the information about its location and time. These signals that are traveling at the speed of light are intercepted by the GNSS receiver which calculates the distance of each satellite from receiver position based on the measurement of time the signal arrives.

$$\text{Distance} = \text{velocity} * \text{time} \qquad (3.3)$$

The GNSS receiver calculates the distance between each one of the satellite and receiver position, the GNSS receiver uses a method called *trilateration* to determine the GNSS receiver position (Figure 3.16). The position thus calculated by GNSS receiver would rely on three accurate measurements; firstly, current time, secondly, position of the satellites, and thirdly, the time delay for the signal. The GNSS time is accurate to about 40 nanoseconds. Higher accuracy can be obtained today by using GNSS in combination with augmentation systems which enable real-time positioning to within a few centimeters.

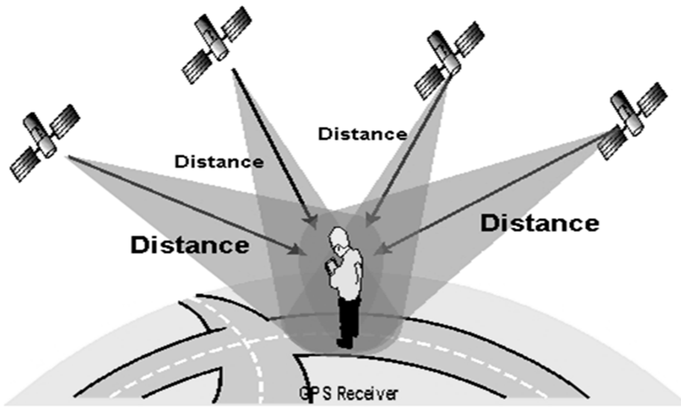

Figure 3.16 Trilateration principle to compute receiver position (Source: https://owaysonline.com/global-positioning-system-on-ships/)

Even though GNSS technology provides us greater advantages, but it still has some limitations. Since GNSS satellite signals are too weak as compared to phone signals, they don't work indoors, underwater, under trees, etc. The line-of-sight of signal from satellite to the GNSS receiver should not be obstructed by high rise buildings and forested areas, as weak signals will give erroneous results.

3.4.3 Various segments of GPS

There are mainly three segments of GPS (Garg, 2019), as shown in Figure 3.17.
(a) Space segment
(b) Control segment, and
(c) User segment

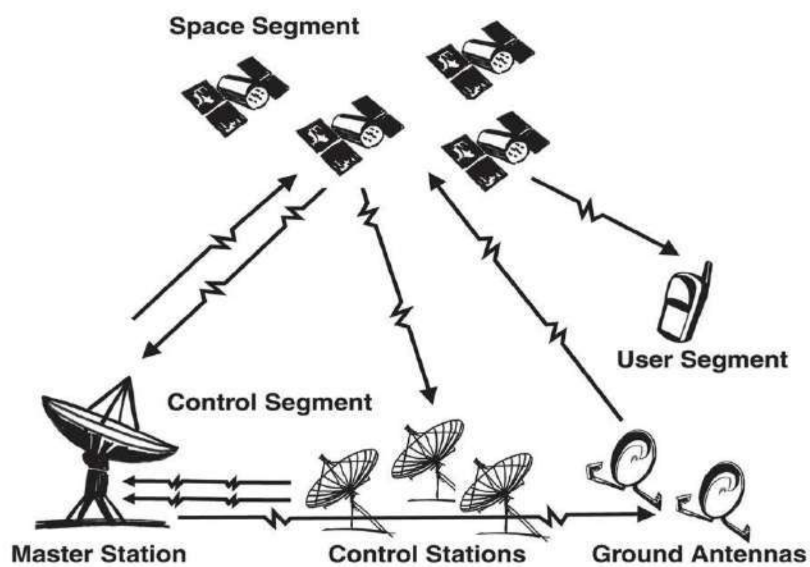

Figure 3.17 Various segments of a GPS (Source: https://shivkumardas.wordpress.com/agri-tech/an-introduction-to-gps-gis-and-its-uses-in-agriculture/)

(a) Space segment

The space segment includes constellation of NAVSTAR Earth orbiting satellites, generally 24 satellites for full global coverage. Thus, there are four satellites moving in 6 orbital planes, as shown in Figure 3.18. The orbital planes are inclined at 55^0 with respect to equator, such that their orbits are separated by 60^0. They revolve around the Earth at the altitude of about 12,000 miles (~20,000 km) above Earth's surface with orbital period of approximately 11 hr 55 minutes (Xu, 2010). This type of configuration provides a greater visibility of five to eight satellites at any given time from anywhere on the Earth. Some of the important features of the GPS satellites are given in Table 3.2.

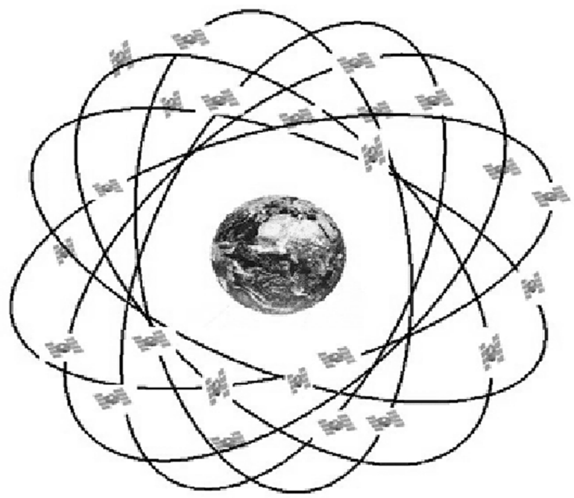

Figure 3.18 The space segment

Table 3.2 Important features of GPS satellites (as on Sept. 2022)

S.No.	Features	Specifications
1	Design life	5 years (with expendables stored for 7 years)
2	On orbit weight	430 kg
3	End-of-life power	400 W
4	Power Source	$5m^2$ solar arrays tracking the sun and 3 Ni-Cd batteries for eclipse
5	Navigation Pay Load	Pseudo Random Noise (PRN) signal assembly, atomic frequency Standard - Caesium beam atomic clocks accurate to 10-14 sec, processor and L band antenna
6	Codes	(a) Precision (P) Code: generated at GPS clock frequency of 10.23 MHz (equivalent to 30 m in range) interpolated to sub-meter level. Repeats itself after 267 days, resolution=100 nanoseconds. (b) Coarse Acquisition (C/A) Code: code sequence frequency of 1.023 MHz (range 300 m) interpolated to few m. Repeats itself every 1 millisecond, resolution = 1 micro second
7	PRN navigation signals on three frequencies	(a) 1575.42 MHz - L1 band - wavelength 19 cm. (b) 1227.6 MHz - L2 band - wavelength 24 cm. (c) 1176.45 MHz - L5 band - within a 24 MHz bandwidth

Each satellite carries four precise atomic clocks; only one of which is used at a time. It also carries three nickel-cadmium batteries, two solar panels, battery charger, S band antenna-satellite control, and 12 element L band antenna-user control. It has a micro-processor on board for limited data processing. At a given time, several satellites can send their signals to a GPS receiver. Each transmission of signal is time-tagged, and contains the satellite's position. The time-of-arrival of signal at GPS receiver is compared with the time-of-transmission, and this time is multiplied by the speed of light to obtain the corresponding distance between that satellite and GPS receiver. The location of the observer is then determined by the intersection of several of these ranges.

The GPS signals contain three different information, as below:

1. **Pseudo random code (PRC)–** It is simply an ID that identifies which satellite is transmitting the information to receiver. The number attached to each signal bar visible on GPS receiver display identifies the satellite sending the signals.

2. **Almanac data–** It contains details of the orbital path of each satellite. The GPS receiver uses this data to determine which satellites it should track. With almanac data, the GPS receiver can concentrate on those satellites it can clearly see, and neglect the ones that would be over the horizon and out of view.
3. **Ephemeris data**– It provides information to the GPS receiver where each satellite should be at available throughout the day. Each satellite will broadcast its own ephemeris data showing the orbital information. Ephemeris data consists of very precise orbital and clock correction information necessary for precise positioning, but it keeps on changing after short time.

(b) Control segment

The control segment is administered by the Department of Defence (DoD), US government, who is responsible for the construction, launching, maintenance and monitoring the performance and health of all GPS satellites launched by them. One master control station is established in USA, and several ground monitoring stations and 4 antenna stations throughout the world, as shown in Figure 3.19. The DoD monitors these stations and tracks all satellites for controlling and predicting their orbits. The master control station is responsible for collecting and tracking the data from the monitoring stations, and computes satellite orbits and clock parameters. Other monitoring stations are responsible for measuring the pseudo range data. This orbital tracking network is used by master control station to calculate the satellite ephemeris and clock correction coefficients, and to forward them to ground antenna. The satellite tracking data from these monitoring stations are transmitted to the master control station for processing.

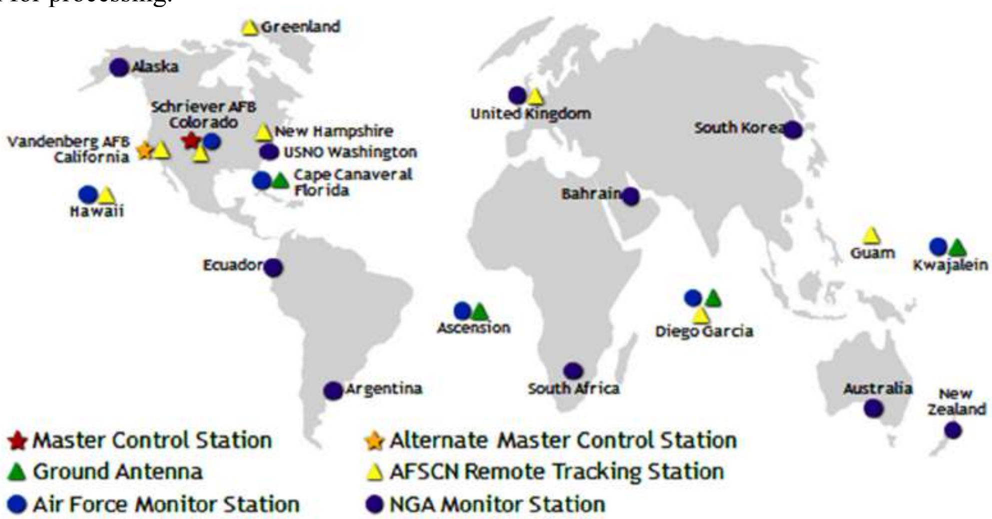

Figure 3.19 The control segment (Source: https://www.gps.gov/systems/gps/control)

(c) User segment

It is the segment where observations are taken by the users for various uses. It consists of GPS receiver unit that receives signals from the GPS satellites (Figure 3.20). The typical receiver is composed of an antenna and a pre-amplifier, radio signal micro-processor, control and display device, data recording unit, and power supply. The GPS receivers convert the satellite signals into position, velocity, and time. The GPS receivers are available in different sizes and shapes. A receiver is often described by its number of channels, signifying how many satellites it can monitor simultaneously (Garg, 2021). Presently, the GPS receivers can operate up to 20 channels. The GPS receiver collects two types of data from satellites to get an exact location i.e., almanac and ephemeris data which are continuously transmitted by the GPS satellites. The almanac gives the exact status of satellites and its approximate orbital information which are used to estimate the visibility of satellites. Ephemeris data gives the accurate information about the orbit of satellite which can be used to calculate the location of a satellite precisely. It is updated every two hours and usually valid for 4 hours. The receiver collects and stores the data.